INFLUENCE OF MANUFACTURING PROCESS ON THE CRITICAL MACHINING PARAMETERS DURING DRILLING.

Redouane Zitoune, Francis Collombet
Laboratoire de Génie Mécanique de Toulouse, IUT Paul Sabatier, Dépt. GMP,
133 C Avenue de Rangueil, BP 67701, 31077 Toulouse Cedex 04, France
redouane.zitoune@iut-tlse3.fr, francis.collombet@iut-tlse3.fr

ABSTRACT

An experimental and analytical study is carried out regarding delamination at the hole exit during the drilling of HexFIT® type glass epoxy composite structures. The plates studied were manufactured using the autoclave and the oven process. The experimental analysis shows that delamination at the hole exit is influenced by the machining conditions on the one hand and by the composite plate manufacturing process on the other hand. Following this, empirical models are developed to predict this delamination for each type of manufacturing process and machining parameter. These models give satisfactory results compared to the experimental values. The maximum relative variation obtained between the values given by the models and those measured (through experiments) is about 9 %. From these empirical models, the critical machining parameters are determined in order to avoid delamination at exit of the hole valid for the two manufacturing processes (oven and autoclave).

1. INTRODUCTION

The aeronautical industry and more generally transportation are in search of materials having functional advantages such as lightness, good mechanical and chemical resistance, long lifespan, reduced maintenance, and short time of manufacture. Taking into account the choices of assembly by drilling carried out in the aeronautical industry, the workability of these materials remains an open problem. Indeed, damage of different nature appears in the structure because of drilling, which harms the lifespan of bolted or riveted assemblies as well as seals [1]. The defects in long fiber composites induced by the operation of drilling are classified according to three zones of appearance: at the entry of the hole, on the wall of the hole and at exit of the hole. The study of the defect on the wall of the hole in UD laminates has already been the object of works based on orthogonal cutting [2]. Thanks to a numerical modelling by finite elements within a nonlinear framework (based on the Fracture Mechanics) and dimensional tests of fields with Digital Image Correlation technique, a dialogue tests/calculation could be established.

Concerning the study of the defect at exit of the hole, several works show that it is influenced by the thrust force produced during drilling and the feed rate of the tool [3, 4]. A numerical 3D model based on fracture mechanics allows the prediction of the critical thrust force (twist drill with two lips) responsible for this defect is developed thanks to the finite element code (SAMCEF software, [3]). In the literature, one finds several techniques to quantify the defect of delamination after machining by drilling [5, 6]. According to [5] the level of delamination is defined as the ratio of D and D_{max} diameters. Knowing that the D parameter represents the nominal diameter of the drilled hole, the D_{max} parameter is the largest diameter characterized by the centre of drilling and a point which defines the widest defect of delamination (see fig. 3). The approach suggested by [6] takes into account the ratio between D and D_{max} like [5] and the ratio between the surface of the hole and the damaged surface as well. A comparison between the techniques of [5] and [6] has been carried out. [6] Shows an overestimation of the size of defect at hole exit, despite of a little difference between the two methods.

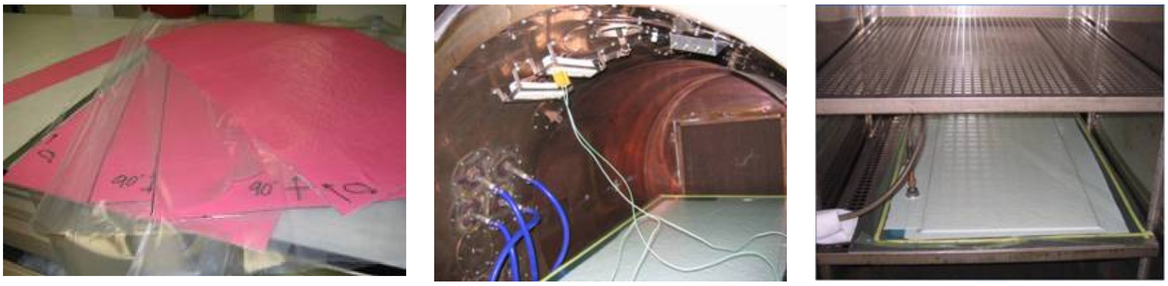
As far as the workability of the material HexFIT® (Hexcel Film Infusion Technology, manufactured by Hexcel Composites) is concerned, these composite materials are made by infusion technique with resin film. They are used for manufacturing large parts in order to reduce costs. Initially, we look at the influence of the manufacturing process of the HexFIT® composite plates in an oven (cycle of temperature with vacuum without pressure application) and in an autoclave (cycle of temperature with vacuum and pressure application) and the machining parameters (spindle speed and feed rate of the cutting tool) on delamination at exit of the hole. We quantify the delamination extent at exit of the hole by the traditional delamination factor (F_d) [5, 6]. A comparison between the measured delamination factors (during composite plate drilling, manufactured in the oven and those manufactured in the autoclave) is proposed for low feed rates (≤ 0.15 mm/rev) and for high feed rates (≥ 0.2 mm/rev).

To predict the delamination factor at exit of the hole, empirical models are developed. The equations obtained are validated by machining parameters (f, N) different from those used for identification. From these empirical models, we have identified the critical machining parameters (cutting speed and feed rate) in order to minimize delamination at exit of the hole.

2. EXPERIMENTAL PROTOCOL

The material used for this test is made from glass/epoxy woven tape HexFIT® manufactured by Hexcel Composites Company. It is based on the principle of Resin Film Infusion by altering twill/twill 2-2, which includes dry pre-impregnated layers covered by a resin film, with a 1 mm ply thickness.

It is therefore a good candidate for large part manufacturing as far as cost reduction is concerned. The machined plates result from two large mother plates for a [0°/90°/90°/0°] stacking sequence, 950 mm x 650 mm dimensions and a theoretical thickness of about 4 mm (see figure 1).



(a) (b) (c)

Figure 1: Manufacturing processes for HexFIT® mother plates with (a) various plies before the draping operation, (b) mould in autoclave and (c) mould in oven.

The manufacturing process used contains two phases. First, the mother-plate is manufactured in an autoclave, followed by the second mother plate, which is manufactured within an oven. The polymerization cycle of the studied plates for the oven process is shown in figure 2. Only a cycle of temperature and a cycle of vacuum are applied for the plates manufactured in oven. For the plates manufactured in autoclave, the same cycle is applied (see in figure 2) and a cycle of pressure of 7 bars is added.

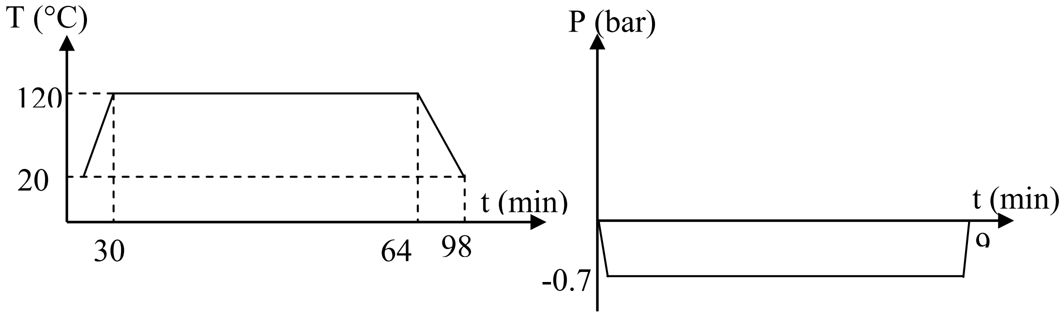


Figure 2: Hexcel Composites polymerization cycle of the plates manufactured with the oven process.

The drilling tests are carried out on a vertical milling machine. It has an automatic speed ranging from 0.05 mm/rev to 0.3 mm/rev and a spindle speed ranging from 320 rev/min to 2700 rev/min. The part to be drilled is embedded on the table of the milling machine with the use of four supports and two fixtures (see figure 3-b). The adjacent support is used to reduce the deflection of the drilled zone during the machining operation (see figure 3-b). The tool is a grade K20 tungsten carbon micro grain. It features three-slopes sharpened to a 118° point angle and a 6 mm diameter. The machining conditions are represented in table 1. The first four machining couples (table 1) are used for the development of the empirical models while the others are used for the validation of the models to be identified (from 0.05 mm/rev to 0.3 mm/rev for the feed rate and from 680 for 2070 the spindle speed).


(a) (b)

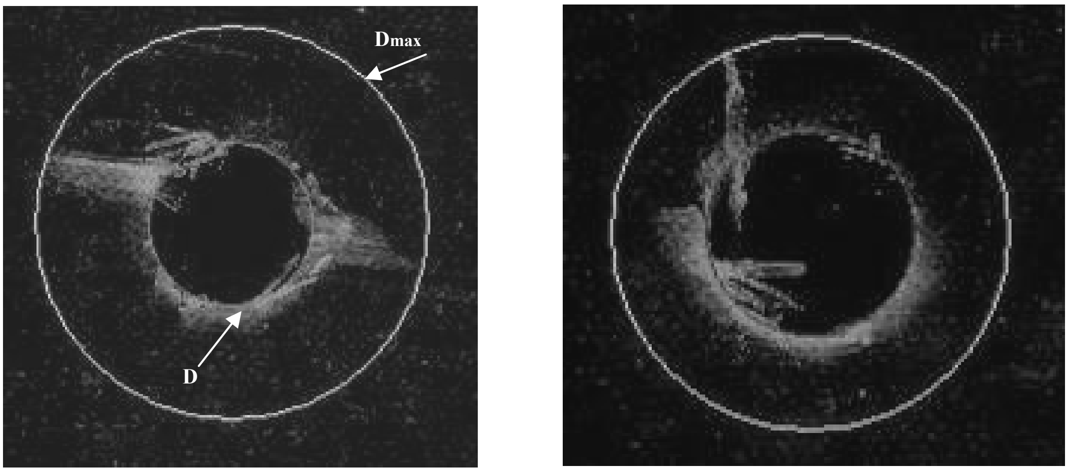
Figure 3: Experimental drilling test device with (a) machining device, (b) fastening of the specimen to be machined.

plate N°	N (rev/min)	f (mm/rev)	plate N°	N (rev/min)	f (mm/rev)
1	**765**	0.05	6	1450	0.1
2	**1050**	0.1	7	2020	0.1
3	**1450**	0.25	8	1050	0.05
4	**2020**	0.3	9	1050	0.25
5	765	0.1	10	1050	0.3

Table 1: Machining parameters for the drilling test (Drill diameter D = 6 mm).

3. RESULTS

The images in figure 4 show the state of the hole exit after the drilling operation. They are obtained with a 3000 pixel traditional scanner for plates machined by drilling (with the feed rate and the number of revolutions of the tool respectively 0.3 mm/rev and 1050 rev/min). Using image analysis software, two concentric circles are traced (one of drill nominal diameter D and the D_{max} diameter characterizing the delamination extent). Delamination at exit of the hole ($F_d = D_{max}/D$) is influenced by the machining conditions and the manufacturing process. More precisely, one notes that this delamination grows as the process advances. Under these machining conditions, the delamination factor for the plate manufactured in oven is equal to 2.05 whereas it is 1.87 for the plate manufactured in autoclave.



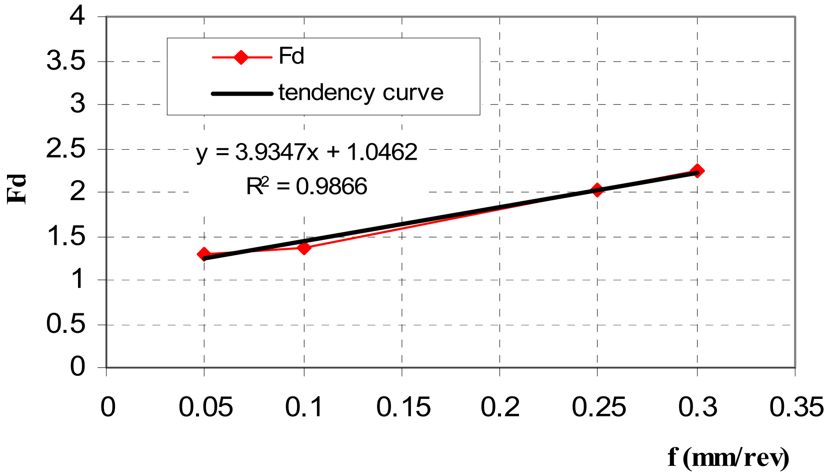
(a) (b)

Figure 4: Pictures representing the defect extension at hole exit with (a) plate manufactured in autoclave, (b) plate manufactured in oven and machining parameters: feed rate f = 0.3 mm/rev, drill diameter D = 6 mm and spindle speed N = 1050 rev/min.

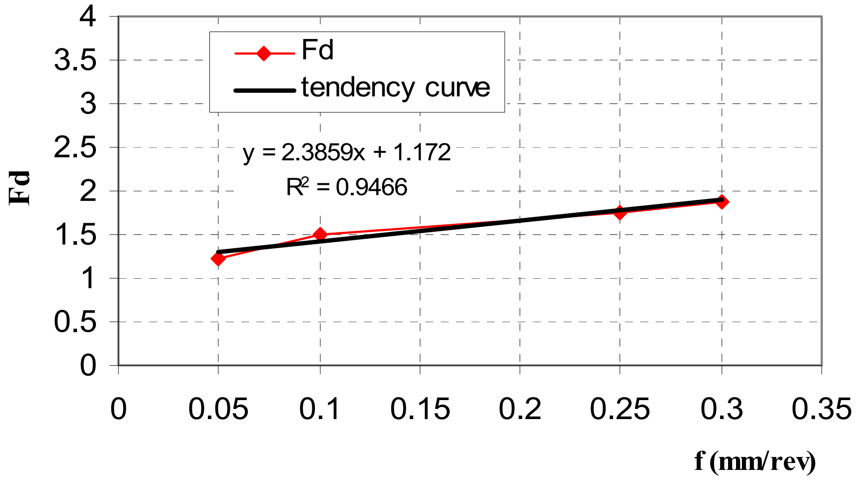
The objective of the function can be fulfilled by optimizing the machining conditions with two variables, namely feed rate (f) and the spindle speed (N). The form of this function is fixed after having identified respectively, the experimental variation of the delamination factor according to the feed rate (for a constant rotational speed) and the delamination factor variation according to the rotational speed (for a constant feed rate). This first analysis is carried out with the two types of manufactured products of the studied composite plates. The results obtained are mentioned below.

Figure 5-a represents the defect evolution at exit of the hole according to the feed rate (for a revolution number of 1050 rev/min and oven process). This defect varies in a quasi linear manner versus the feed rate. The tendency curve also illustrates this. Each point on the curve of the delamination factor represents a six value arithmetic average. Similar observations are observed in the case of the plate machining manufactured in the autoclave.

Therefore for the two processes of manufacture studied, the defect at exit of the hole varies linearly according to the feed rate. A comparison between the delamination factors measured at the time of the drilling of the composite plates manufactured in the oven and those manufactured in the autoclave shows that they are almost identical when the speed is low (≤ with 0.15 mm/rev). However, for higher feeds rate (≥ with 0.2 mm/rev), the delamination factors measured on plates polymerized in the autoclave are smaller than those measured on plates polymerized in oven (see figure 5-a, figure 5-b).



(a)



(b)

Figure 5: Variation of the delamination factor at the exit of the hole according to feed rate and for machining parameters: spindle speed N= 1050 rev/min, drill diameter D = 6 mm with (a) oven process, (b) autoclave process.

If we fix the feed rate and we vary the number of rotational speeds, the delamination factor at the hole exit grows slightly. This variation can be approximated to a linear evolution, especially in the case of the plate machining polymerized in an autoclave (see in figure 6). In the case of machining polymerized with the oven, the tendency curve is difficult to be interpreted (distance of a point on the curve corresponding to the F_d evolution according to the revolution number). This can be due to the presence of a very porous zone in the vicinity of the matter removal area which leads to a rather significant delamination. It should be noted that the porosity test analysis by the calcination method (in accordance with the standard NF IN ISO 1172) shows that the plates manufactured in oven have an air void proportion of about 12 %. Those manufactured in an autoclave have an air void proportion of about 3 %.

4 EMPIRICAL MODELS

Knowing that the delamination factor at the hole exit varies linearly according to the feed rate and the revolution number, one must determine an analytical function representative of the delamination factor according to the cut parameters (f and N). This function is a multiple linear regression (with two variables) of the 1st order. We suppose the interaction between the cut parameters, see equation 1:

$$F_d = a_{11}.f + a_{22}.N + a_{33}.f.N + a_{44} \qquad (1)$$

with $a_{11} > 0$ and $a_{22} > 0$.

The resolution method used in this study is iterative using a resolution algorithm combined with gradient type. The aim is to find the function which represents a minimum in terms of difference between the measured values and those given by the analytical function under constraint. Initially, the results related to the machining of the plates resulting from the hermetically-sealed process and the associated validations are presented. Following that, the results of the machining of the manufactured plates with the autoclave process and their validations are presented.

a. Process autoclave

The obtained results in the case of a manufactured plate in an autoclave are calculated respectively in the expression of equation 2:

$$F_d = 0.580 + 2.9506.f + 0.00077.N - 0.00178.f.N \qquad (2)$$

The obtained equation is validated by couples of machining parameters (f, N) different from those used for the identification (see table 2). A comparison between the delamination factors (obtained using this empirical model and those measured experimentally) shows that the maximum relative variation obtained is about 8. Thanks to reverse methods from equation 2, one can identify the critical machining parameters. The critical machining parameters are the ones for which D_{max} = D (see figure 4) and therefore F_d = 1. The cartography in Figure 6 represents the distribution of the delamination factor at various feed rates and spindle speeds. The intersection of this cartography with the plan F_d = 1 represents a curve that characterizes the points relative to the critical machining parameters (see figure 7).

f (mm/rev)	N (rev/min)	$F_{d\ \text{experimental}}$	$F_{d\ \text{analytical (eq. 2)}}$	E %
0.1	1450	1.645	1.737	5.292
0.25	1050	1.759	1.662	5.555
0.3	1050	1.877	1.716	8.576

Table 2: Relative variation between experimental and analytical delamination factor for various machining parameters (drill diameter D = 6 mm) and for the empirical model with a plate manufactured in autoclave.

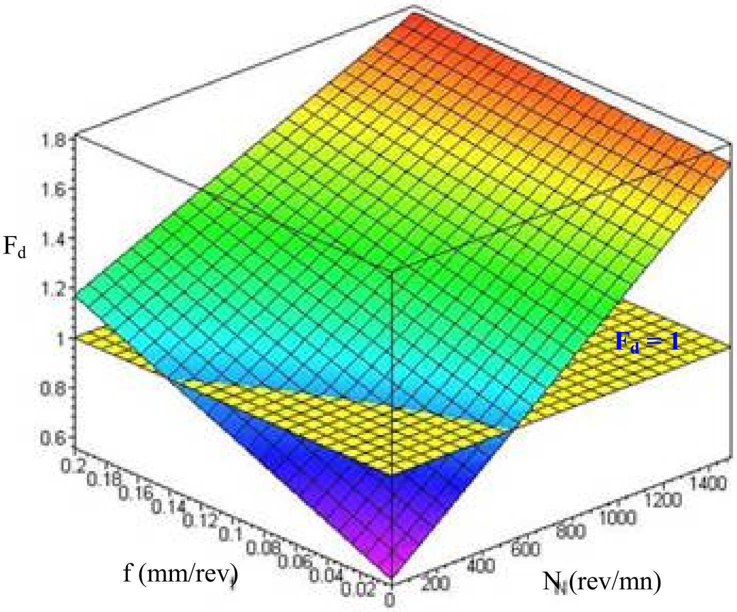


Figure 6: Surface representation of the critical machining parameters for a plate manufactured in autoclave giving by equation 2.

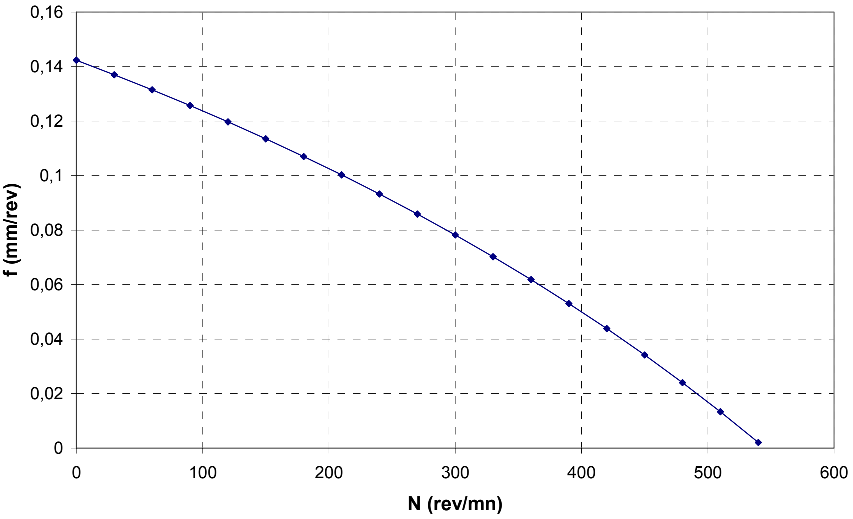


Figure 7: Critical machining parameters for a plate manufactured in autoclave with the critical feed rate $f_{critical}$ (mm/rev) versus the critical spindle speed $N_{critical}$ (rev/min).

b. Process oven

The results obtained in the case of a plate manufactured in the oven are calculated respectively in the expression of equation 3:

$$F_d = 0,809 + 1,9608 \cdot f + 0,00028 \cdot N + 0,000589 \cdot f \cdot N \tag{3}$$

A comparison between the delamination factors obtained using this empirical model (see equation 3) and those measured experimentally shows that the maximum relative variation is about 7 %. As in the case of machining of the plates manufactured in autoclave, if we seeks to identify the critical machining parameters (by reverse method), it is enough to consider $F_d = 1$ (F_d given by equation number 3). The cartography in Figure 8 represents the distribution of the delamination factor by feed rate and spindle speed for a plate manufactured in the oven. The intersection of this cartography with the plan $F_d = 1$ represents a curve that characterizes the points relative to the critical machining parameters (see figure 9).

f (mm/rev)	N (rev/min)	$F_{d\ \text{experimental}}$	$F_{d\ \text{analytical (eq. 3)}}$	E %
0.1	1450	1.614	1.500	7.02
0.1	2020	1.681	1.695	0.81
0.05	1050	1.301	1.235	5.07

Table 3: Relative variation between experimental and analytical delamination factor for various machining parameters (drill diameter D = 6 mm) and for the empirical model and a plate manufactured in oven.

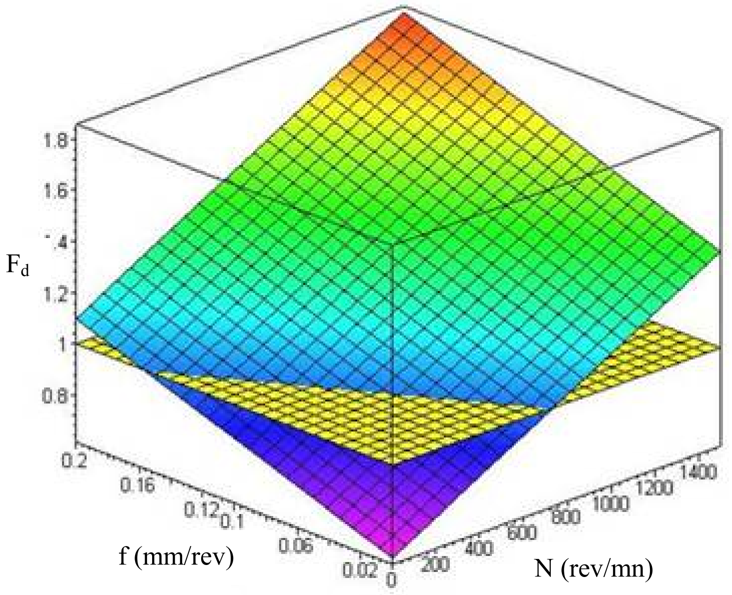


Figure 8: Surface representation of the critical machining parameters for a plate manufactured in oven by the equation number 3.

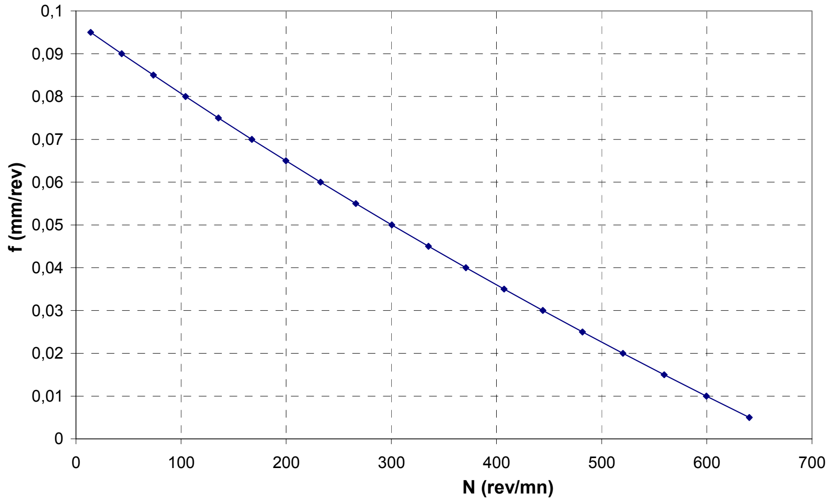


Figure 9: Critical machining parameters for a plate manufactured in oven with the critical feed rate f_{critical} (mm/rev) versus the critical spindle speed N_{critical} (rev/min).

The suggested empirical models show that the delamination factor at the hole exit is influenced by the manufacturing process of the studied composite plates. This explains the importance of the manufacturing process for the optimization of the machining parameters. Thus empirical models of the literature have to be used carefully if manufacturing process information is not defined. For the two studied manufacturing processes (oven and autoclave), we note the two models show that the delamination factor is proportional at the feed rate and the spindle speed. This observation consolidates the results of [6, 7]. The optimal critical machining parameters ($f_{critical}$ and $N_{critical}$) lead to no delamination at the hole exit during machining both for manufactured plates in oven and in autoclave. Graphically speaking, these optimal machining parameters represent the intersection point between the machining critical conditions both for plates manufactured in oven and in autoclave. This optimal critical point is characterized by a 0.024 mm/rev feed rate and a 480 rev/min spindle speed. The machining using those critical machining parameters shows a good hole quality. Moreover these critical machining parameters do not show any defect in the hole entry (delamination type of the first ply).

5. CONCLUSIONS

An experimental and analytical studies were carried out to analyse the delamination at the hole exit during composite material drilling made of long fibres with epoxy matrix with a twist drill containing two tungsten carbide lips. The experimental and the analytical results have shown that delamination at the hole exit (induced by the drilling operation) is influenced on the one hand, by the choice of the machining parameters (f and N) and on the other hand, by the manufacturing process of the composite structures. The experimental results show that, for higher feed rates ($\geq$ 0.2 mm/rev), the measured delamination factors on plates polymerized in the autoclave are smaller than those measured on plates polymerized in oven. Empirical models to predict the delamination factor at the hole exit are developed. For that purpose, the quadratic error is minimized between experimental measurements and analytical calculation. The maximum relative variation obtained between the values given by the models and those measured through experiments is about 9 %. From these empirical models we could identify the critical machining parameters which give a delamination factor equal to 1 for each studied manufacturing process. The composite plate machining with the critical machining parameters is of good quality.

6. REFERENCES

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